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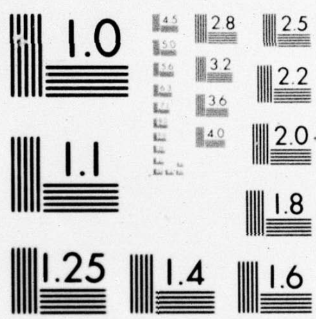

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FATIGUE EVALUATION OF AUTO TIG WELD JOINTS FOR HEAT EXCHANGER APPLICATIONS

J. J. Bethke
Air Vehicle Technology Department
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Fatigue tests were performed to compare the dynamic load response of auto-TIG step pulse welds with currently used manual electric arc welds in heat exchanger joint applications. The new auto-TIG weld technique for fabricating the joints, designed by Naval Ship Engineering Center, Philadelphia Division has been shown to be more time and cost effective. Full-scale joints were used to test specimens representing the heat exchanger cooling tube to end wall assembly and consisted of a over

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2.25 Cr - 1.0 Mo heat resistant steel tube of 3.18 cm (1.25 in.) outside diameter welded to a 1.25 Cr - 1.0 Mo end wall section containing an oversized 3.18 cm (1.25 in.) diameter hole.

Direct stress, tension-tension (R = 0.1) cyclic loading was performed in an electro-hydraulic closed loop test machine at a test frequency of 2 Hz. No significant difference between the manual and auto-TIG welded specimens was found with respect to resistance to dynamic axial loading. Both type specimens achieved a fatigue strength of one million cycles of about 66.7 Kn (15,000 lbf) (which represents a tube stress of 180 MPa (26 ksi)). However, in considering the complete joint configuration, the area of the tube expansion fit into the end wall hole was found to be a competing design limitation (with the weld) with respect to dynamic axial loading and was determined to be the prime area of failure under dynamic bending loads.

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INTRODUCTION

This study was initiated by the Naval Ship Engineering Center, Philadelphia Division (NAVSECPHILADIV) for the purpose of comparing the dynamic load response of newly developed machine made weld joints with current manually made weld joints for heat exchanger applications. Currently, welds are made manually by the electric arc process to join heat exchanger cooling tubes to end walls in naval boilers. The new design and procedures would utilize an automatic TIG step pulse weld process (auto-TIG). This study is part of a larger NAVSECPHILADIV program aimed at characterizing the new auto-TIG weld technique with respect to design, mechanical properties, installation procedures, serviceability, and cost. Use of the new auto-TIG technique would provide several advantages over manual welding resulting from the comparative ease in making consistently good quality welds. Due to accessibility problems, consistently good quality manual welds are difficult to achieve requiring the most highly qualified welders. Thus, significant reduction in cost and time could be realized using the auto-TIG process as well as benefits with respect to rework and repair - that is, repairs could be made at field activities rather than at shipyards as currently required.

The purpose of this study was to compare the fatigue properties of material produced by the auto-TIG and electric arc processes to determine if there wasaany penalty in fatigue resistance of the weld joint using the auto-TIG process. To do this, full scale joints were used as test specimens representing the cooling tube to end wall joint. Both manual and machine welded specimens were tested. Cyclic life at various load levels as well as the fatigue strength at one million cycles were determined. Primary emphasis was placed on axially loaded fatigue tests since this would provide a good test of the weld material. One specimen of each weld configuration was also dynamically loaded in bending.

TEST SPECIMENS

The manual welded and auto-TIG machine welded test specimens, shown in Figures 1 - 4, consist of a 2-1/4 Cr- 1 Mo heat resistant steel tube welded to a 1-1/4 Cr - 1 Mo end wall section. The two specimen types are identical except for the weld design and technique used in the attachment of the tube to the end wall. Nominal dimensions are the same for both specimen types with respect to tube length, outside and inside diameters, end wall base section thickness and hole diameter. Prior to welding,the tubes are inserted into the oversized hole in the end wall section and mandrel expanded to form a snug fit.

The manual welds are made by electric arc process using 2-1/4 Cr - 1 Mo steel filler material. The tube is inserted flush with the backside of the end wall section which contains a machined J-groove. The machine made welds utilize the automatic TIG step pulse process to provide a fusion weld between the tube and end wall sections with the tube recessed from the end wall backside.

EXPERIMENTAL PROCEDURE

A. Direct Stress Tests

Direct stress fatigue tests were performed in a 1,780 kN (400,000 lb.) capacity electrohydraulic closed loop fatigue test machine in the 178 kN (40,000 lb.) load range. Servo control was performed using MTS equipment while test load programming was made through an EMR 1641 digital profiler with peak load accuracy of 2% maintained by an EMR 1643 limits detector. Constant amplitude tension-tension cyclic loading was applied, R = .1 (R = load ratio = minimum cyclic load/maximum cyclic load), using a sine wave function. Tests were conducted in an air environment at room temperature at a cyclic frequency of 2 Hz. The complete test apparatus is pictured in Figure 5 while the digital programming and readout panel is shown in Figure 6 during a test run.

Initial tests, using direct clamping of both ends of the test specimen, were unsatisfactory because of the high occurrence of tube failures at the base section due to misalignment. Subsequently, tests were run using a specially designed spherical seat fixture to support the base section of the test specimen and provide some degree of self-alignment. This spherical bearing is shown in Figure 7 in an "exploded view" manner installed on a test specimen. The mating surfaces of the spherical bearing seat were polished to a 406 nm (16 μ in) finish, sandblasted, and coated with MoS_2 solid film lubricant. Figure 8 shows the gripping arrangement in the test machine during testing. The free end of the tube was clamped directly by the upper crosshead hydraulic grips and contained a removable metal plug insert to prevent crushing of the tube. Hydraulic grip pressure in both upper and lower jaws was approximately 41 MPa (6,000 psi).

B. Bend Tests

Bending fatigue tests were performed in a 22.2 kN (5,000 lb.) capacity Sontag Universal fatigue test machine of the rotating eccentric mass type with electronic automatic preload maintainer. This machine, along with the special fixturing designed to provide cantilever bending of the test specimen, is shown in Figures 9 and 10. Constant amplitude cyclic loading, R = .1, was applied at the tube free end to provide maximum outer fiber stresses in the top surface of tube at the clamped base section. Dynamic loads are applied to the loading platen by the rotating eccentric weight and are superimposed on a mean load set and maintained by the preload mechanisms. The test specimen is attached to the loading platen with a 2.54 cm (1 - in.) diameter bolt threaded into the free end of the tube and inserted through a spherical bearing. Tests were conducted in an air environment at room temperature with a sine wave cyclic frequency of 30 Hz.

RESULTS AND DISCUSSION

A. Direct Stress Tests

A summary of the direct stress fatigue test results is shown in Tables I and II for the manual and auto-TIG welded specimens, respectively. It can be seen that two different types of failure occurred in both weld joint configurations. These can be characterized as fracture of the weld joint and fracture of the tube at the point of tube entrance into the end wall section away from the weld. The load - cyclic life plot for the specimens that failed in the weld is shown in Figure 11. This data shows very similar dynamic load response for both the manual and auto-TIG type welds - *a fatigue strength* at one million cycles of about 66.7 - 75.6 kN (15,000 - 17,000 lb.). With the exception of the one data point at 89 Kn (20,000 lb.) maximum cyclic load, all the data fell within a very narrow band. This one exception might indicate somewhat greater scatter in the manual welded joints than in the auto-TIG welded joints but more extensive tests would have to be run to determine this. Representative weld failures for the manual and auto-TIG welded joints are shown in Figure 12. The center tubes of Figure 13 shows these at slightly higher magnification. The manually welded joints failed in the tube in the heat affected zone (3.2 - 6.4 mm (1/8" - 1/4") from the end of the tube) with the fracture propagating perpendicular to the tube axis to complete failure. The auto-TIG welded joint failures initiated in the weld toe, at the outside diameter of the tube, followed by a small amount of crack propagation perpendicular to the tube axis with final fracture by shear (overload) through the weld material at about 45° to the tube axis.

As mentioned earlier, a significant number of test specimens of both weld types did not fail at the weld but rather in the tube as it enters the end wall section. Examples of this are shown in Figures 13 and 14. These failures are attributed to the combined effects of tube dimensional changes in the area of the end wall and slight imposed bending loads. Changes in the tube diameter occur in the area of the end wall due to the expansion fit of the tube into the end wall hole prior to the welding operation. This yields an area of stress concentration. An examination of several specimens, the results of which are presented in Table IV, showed that while tubes from both type weld joints had a gradual diameter increase (of approximately .5 mm (0.020 - in.))going into the end wall, the auto-TIG welded joint tubes also exhibited a sharp surface discontinuity of .05 - .13 mm (2 - 5 mils) at the point of tube entrance into the end wall section. This difference in tube geometry going into the end wall must be attributed to process variations in the fabrication of the two weld joint types. Bending loads are imposed on the tube due to misalignment between the top and bottom grips - perfect alignment cannot be achieved even with the use of the spherical gripping fixture. The random occurrence of tube failures is seen as an indication of the sensitivity of the joint design in the expanded tube area to dynamic loading.

Among the tube failures, the manually welded specimens outlasted the auto-TIG welded specimens, Figure 15. In this regard, the better performance of the manually welded specimens is thought to be due primarily to the nature of the tube diameter changes entering the end wall. Since the manually welded specimens do not contain the sharp surface discontinuity exhibited by the auto-TIG specimens, they represent less of a stress concentration and therefore survive a greater number of stress reversals.

B. Bend Tests

Table III is a summary of the bending fatigue test results. These tests were run to satisfy sponsor requirements but were not expected to be a satisfactory test of the weld since the end wall effectively acts as a clamping device for the tube providing a cantilever bending test of the tube. Failure of these specimens did in fact occur as expected and thus provided no real information for comparison of the two different type welds. Cyclic life at 276 MPa (40,000 psi) test stress was essentially the same for both the manual and auto-TIG welded specimens, about $1.4 \pm .14 \times 10^6$ cycles, reflecting only the inherent resistance of the tube to dynamic loading. Figure 16 shows a bend specimen in the test rig after failure and indicates the point of fracture in the tube at the end wall.

CONCLUSIONS

1. There is no significant difference between the manual and auto-TIG welded specimens of this study with respect to resistance to dynamic axial loading. Axial loading of the joint does test the weld.

2. Cyclic cantilever bending of the joint does not test the weld.

3. Considering the entire joint configuration, the area of the tube expansion fit into the end wall hole represents a competing design limitation (with the weld) with respect to dynamic axial loading and is the prime area of failure under dynamic bending loads.

TABLE I

DIRECT STRESS FATIGUE TEST RESULTS: MANUAL WELDS

Specimen No.	Test Load, kN (lbf) Max.	Min.	Max. Tube MPa Stress, (ksi)	Cycles to Failure	Remarks
12	155.7 (35,000)	15.6 (3,500)	420 (60.9)	10,529	- Failed at weld - Spherical seat fixture not used
9	89.0 (20,000)	8.9 (2,000)	241 (35.0)	790,747	- Failed in tube - Spherical seat fixture not used
7	133.4 (30,000)	13.3 (3,000)	360 (52.2)	85,410	- Failed in tube - Spherical seat fixture not used
2	89.0 (20,000)	8.9 (2,000)	241 (35.0)	652,269	- Failed at weld
6	80.0 (18,000)	8.0 (1,800)	216 (31.3)	130,331	- Failed at weld
8	66.7 (15,000)	6.7 (1,500)	180 (26.1)	1,093,526	- Runout -no failure
4	122.3 (27,500)	12.2 (2,750)	330 (47.8)	167,510	- Failed in tube
3	89.0 (20,000)	8.9 (2,000)	241 (35.0)	99,394	- Failed at weld
1	89.0 (20,000)	8.9 (2,000)	241 (35.0)	118,491	- Failed at weld
5	66.7 (15,000)	6.7 (1,500)	180 (26.1)	1,020,000	- Runout - no failure
Repeat	155.7 (35,000)	15.6 (3,500)	420 (60.9)	19,682	- Failed in tube
11	75.6 (17,000)	7.6 (1,700)	204 (29.6)	612,897	- Failed in tube

TABLE II

DIRECT STRESS FATIGUE TEST RESULTS: AUTO-TIG WELDS

Specimen No.	Test Load, kN (lbf) Max.	Min.	Max. Tube MPa Stress, (ksi)	Cycles to Failure	Remarks
U	89.0 (20,000)	8.9 (2,000)	241 (35.0)	201,382	- Failed in tube - Spherical seat fixture not used
V	155.7 (35,000)	15.6 (3,500)	420 (60.9)	11,041	- Failed in weld - Spherical seat fixture not used
I	66.7 (15,000)	66.7 (1,500)	180 (26.1)	1,000,000	- Runout - no failure - Spherical seat fixture not used
T	133.4 (30,000)	13.3 (3,000)	360 (52.2)	43,575	- Failed in tube
L	89.0 (20,000)	8.9 (2,000)	241 (35.0)	101,963	- Failed in weld
S	66.7 (15,000)	6.7 (1,500)	180 (26.1)	1,221,234	- Runout - no failure
P	75.6 (17,000)	7.6 (1,700)	204 (29.6)	524,659	- Failed in tube
Q	80.0 (18,000)	8.0 (1,800)	216 (31.3)	379,684	- Failed in tube
R	80.0 (18,000)	8.0 (1,800)	216 (31.3)	596,661	- Failed in tube
J	80.0 (18,000)	8.0 (1,800)	216 (31.3)	206,732	- Failed in weld
K	75.6 (17,000)	8.0 (1,700)	204 (29.6)	681,265	- Failed in weld

TABLE III

BENDING FATIGUE TEST RESULTS

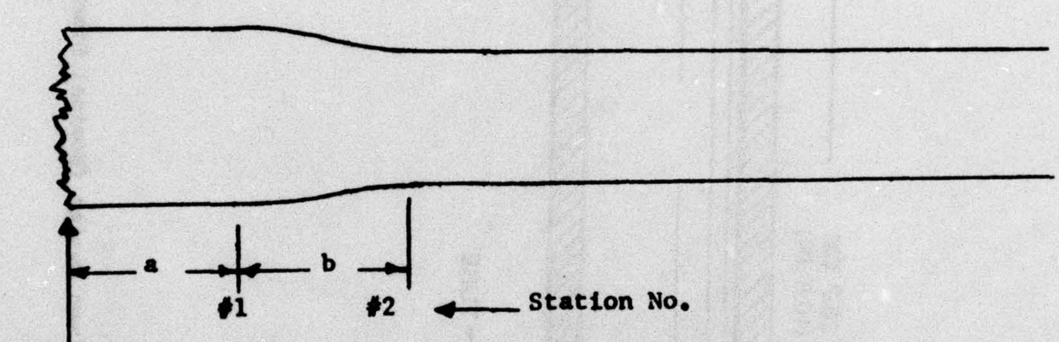
Specimen No.	Weld Type	Test Loads, kN (lbf) Max.	Min.	Max. Tube MPa Stress* (ksi)		Remarks
0	Auto-TIG	1.36 (305)	.14 (30.5)	172 (25.0)	3,200,000	- Runout - No failure
Repeat	Auto-TIG	1.90 (427)	.19 (42.7)	241 (35.0)	2,417,000	- Failed in tube at base section
M	Auto-TIG	2.17 (488)	.22 (48.8)	276 (40.0)	1,326,000	- Failed in tube at base section
10	Manual	2.17 (488)	.22 (48.8)	276 (40.0)	1,596,000	- Failed in tube at base section

* Outer fiber tensile stress in tube at base section.

TABLE IV

TUBE DIMENSIONAL CHANGES DUE TO EXPANSION FIT
(From Specimens That Failed In The Weld)

Tube Profile



Specimen No.	O.D. at Station, cm (inch) #1	#2	"a" cm (inch)	"b" cm (inch)	Remarks
1	3.221 (1.268)	3.170 (1.248)	4.45 (1.75)	1.27 (.50)	Fractured 3.2 cm (.125 in.) from end of tube.
2	3.213 (1.265)	3.162 (1.245)	3.81 (1.50)	1.27 (.50)	Fractured 3.2 cm (.125 in.) from end of tube.
3	3.221 (1.268)	3.162 (1.245)	2.54 (1.0)	.89 (.35)	Fractured 6.4 cm (.250 in.) from tube end.
12	3.175 (1.250)	3.127 (1.231)	2.29 (.90)	1.90 (.75)	Fractured 6.4 cm (.250 in.) from tube end.
K	3.226 (1.270)	3.175 (1.250)	2.54 (1.0)	1.27 (.50)	.05 mm (2 mil) ridge around circumference at 1.90 cm (.75 in.) from tube fracture.
L	3.221 (1.268)	3.150 (1.240)	2.79 (1.1)	1.27 (.50)	.08 mm (3 mil) ridge around circumference at 1.90 cm (.75 in.) from tube fracture.
V	3.205 (1.262)	3.137 (1.235)	1.90 (.75)	1.90 (.75)	.05-.13 mm (2-5 mil) ridge around circumference at 1.90 cm (.75 in.) from tube fracture.

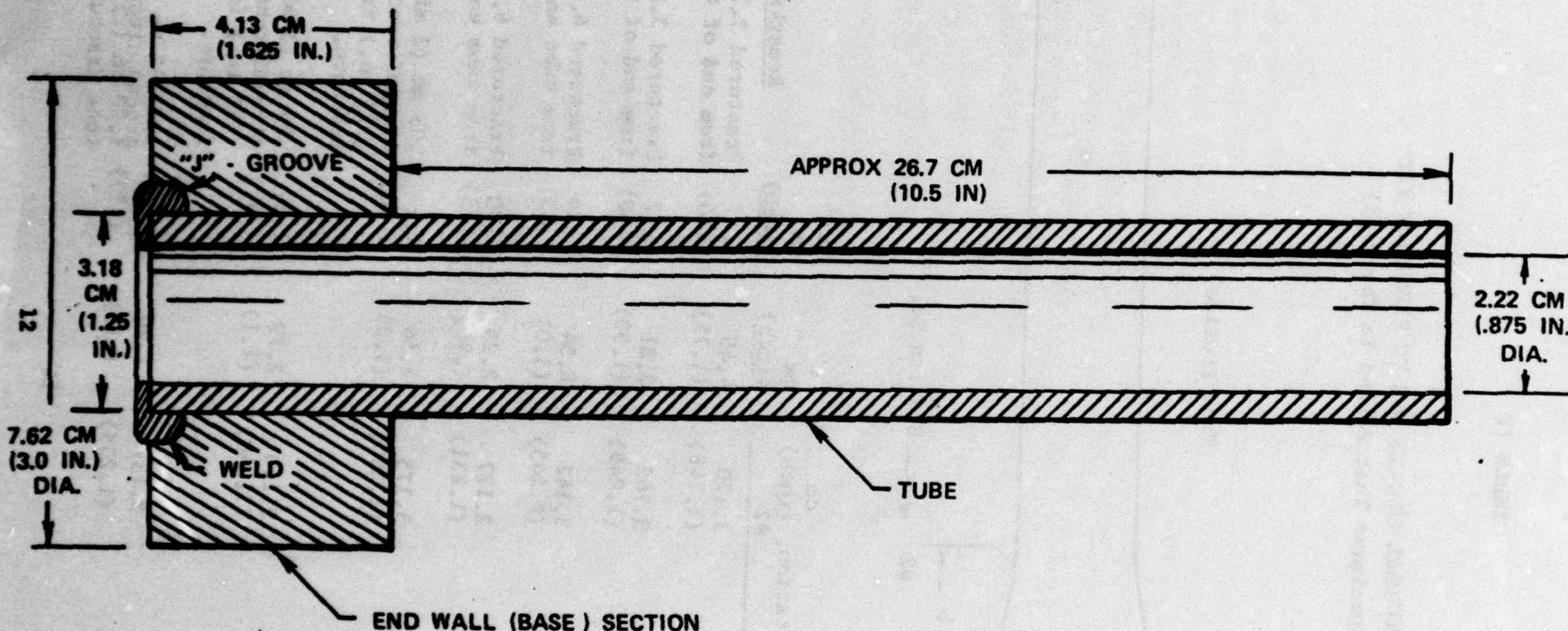


Figure 1. Manually Welded Test Specimen Design (Nominal Dimensions)

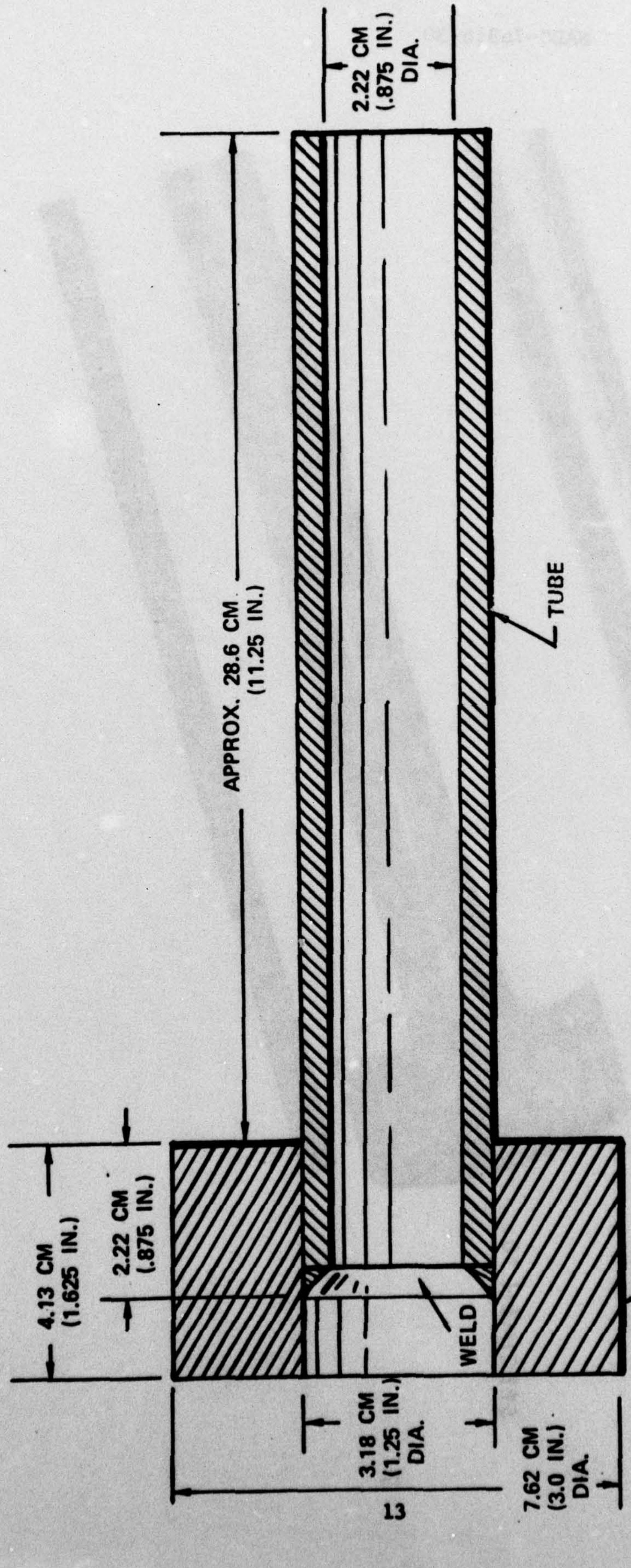


Figure 2. Machine Welded Test Specimen Design (Nominal Dimensions)

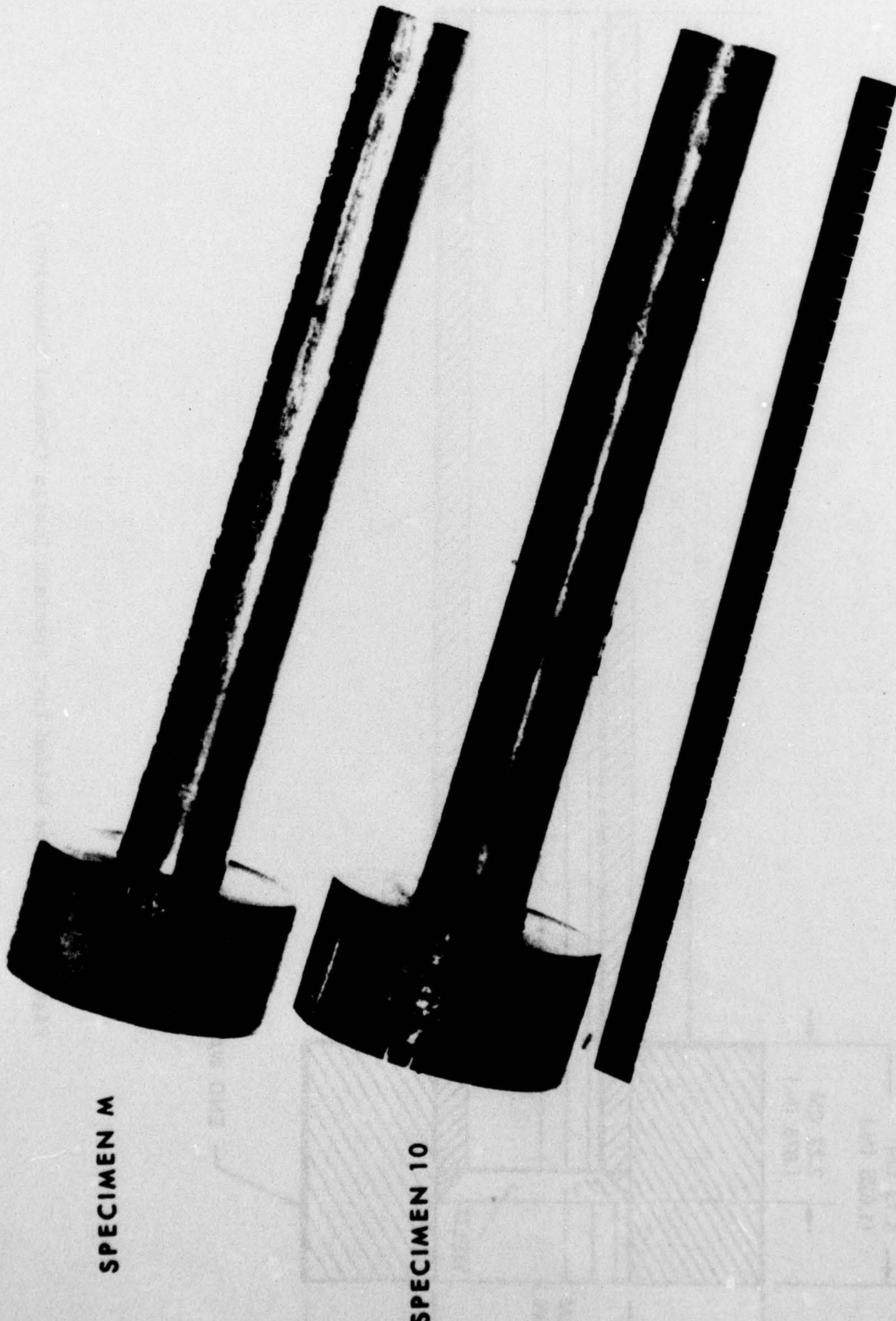


Figure 3. Profile of Test Specimens: Auto-TIG (Specimen M) and Manually (Specimen 10) Welded

Figure 4. End View of Test Specimens Showing Welds

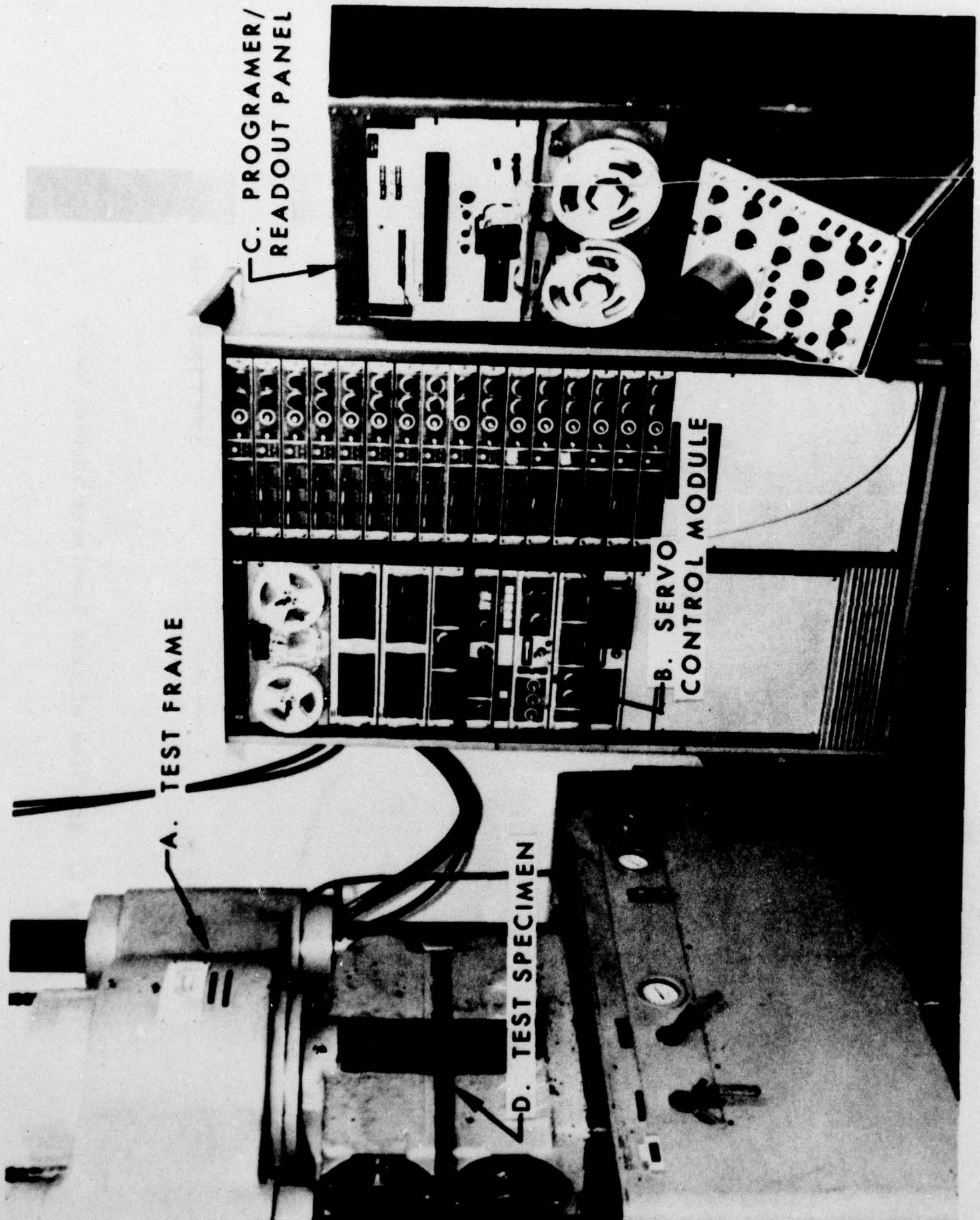


Figure 5. Set-Up for Direct Stress Fatigue Tests

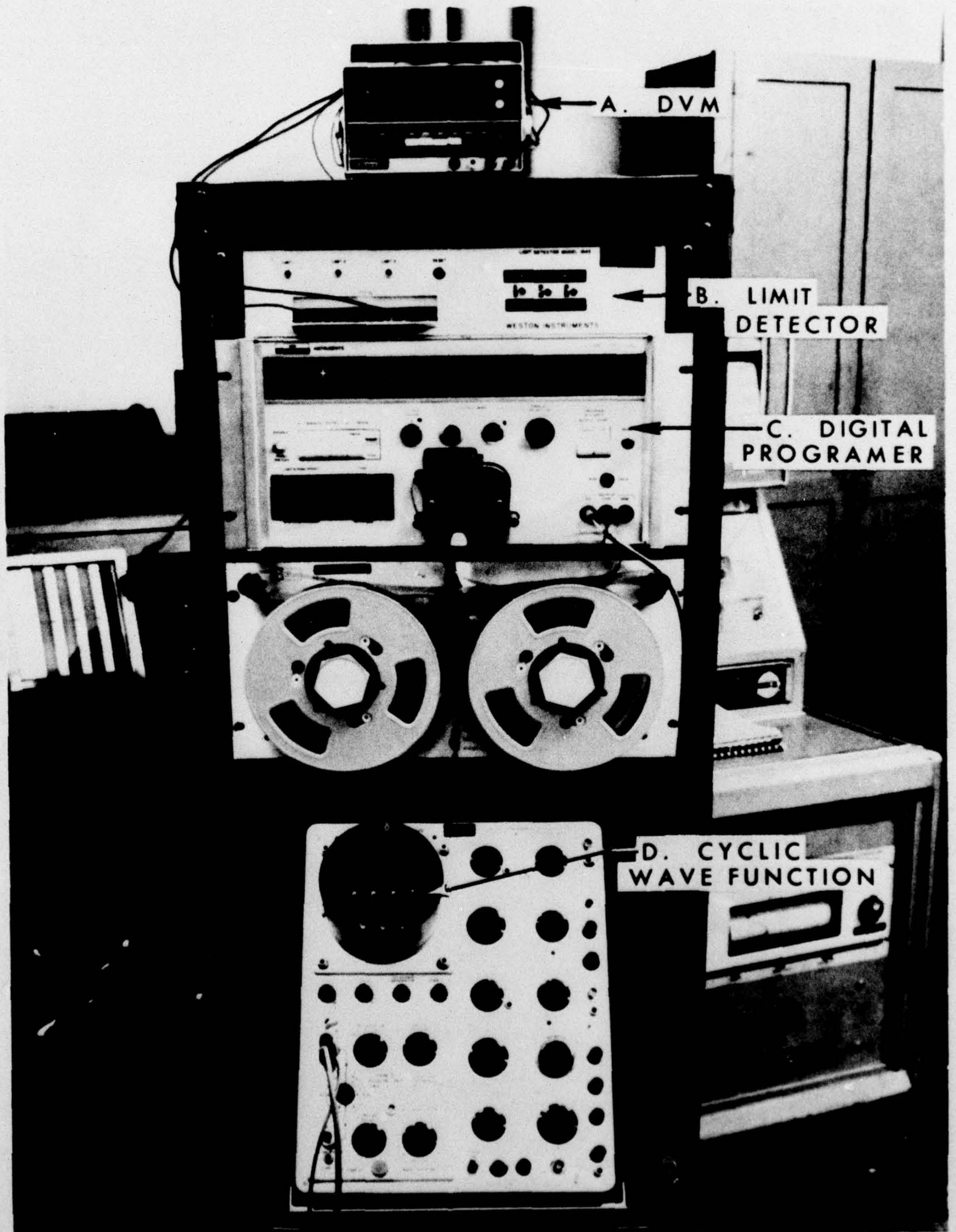


Figure 6. Programmer/Readout Panel During Test Showing Cyclic Wave Function

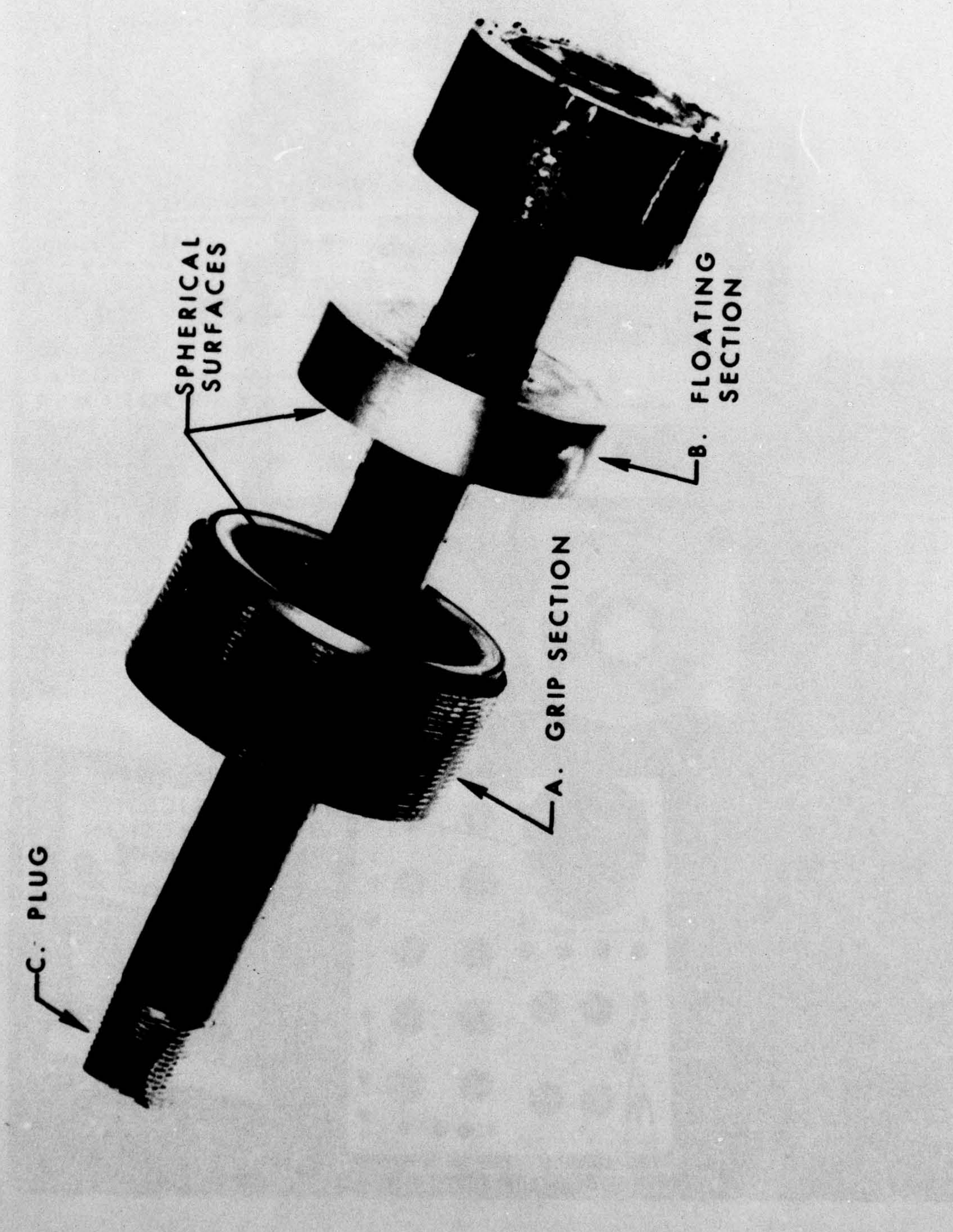


Figure 7. Spherical Seat Test Fixture with Test Specimen

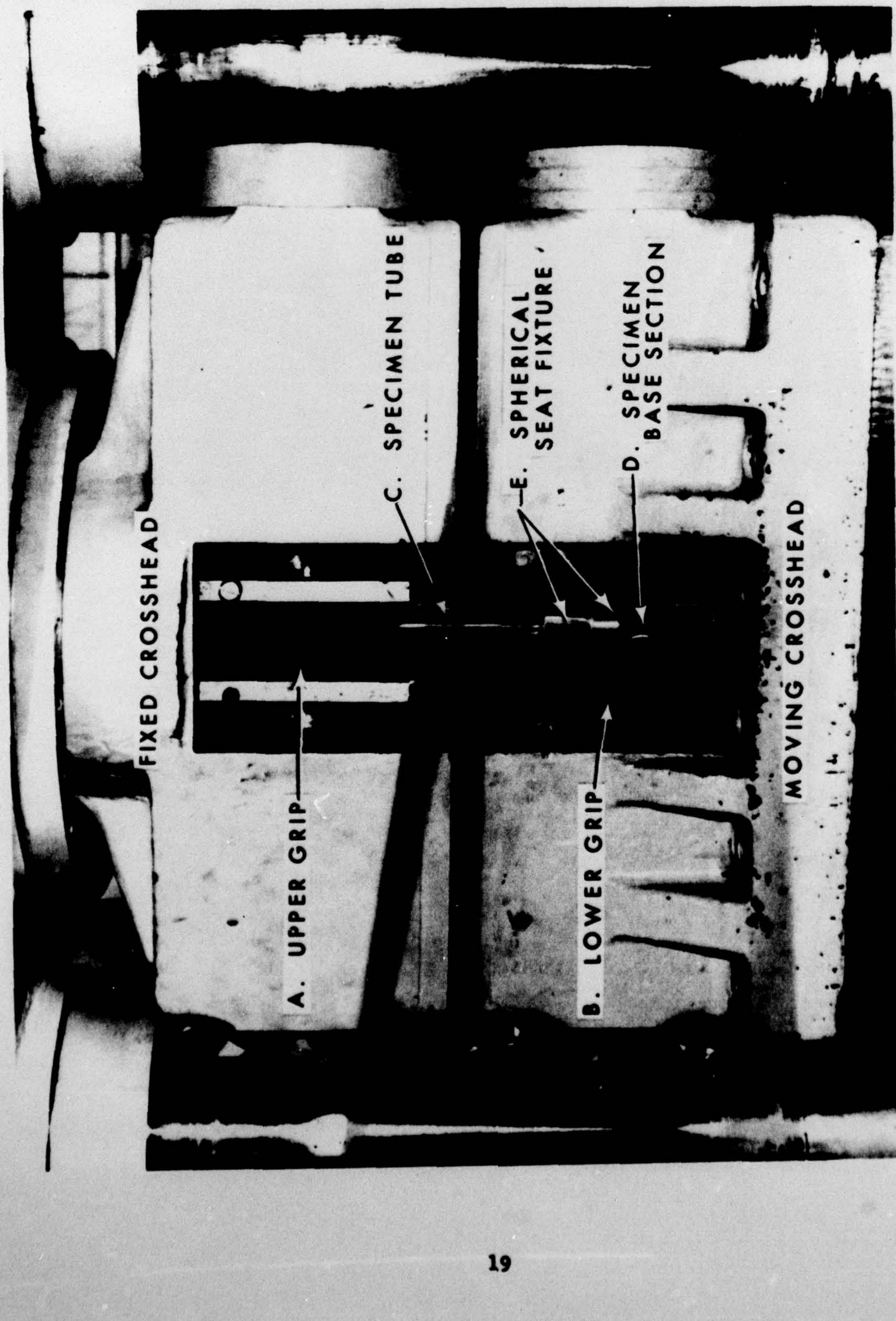


Figure 8. Specimen Gripping Arrangement in Test Frame

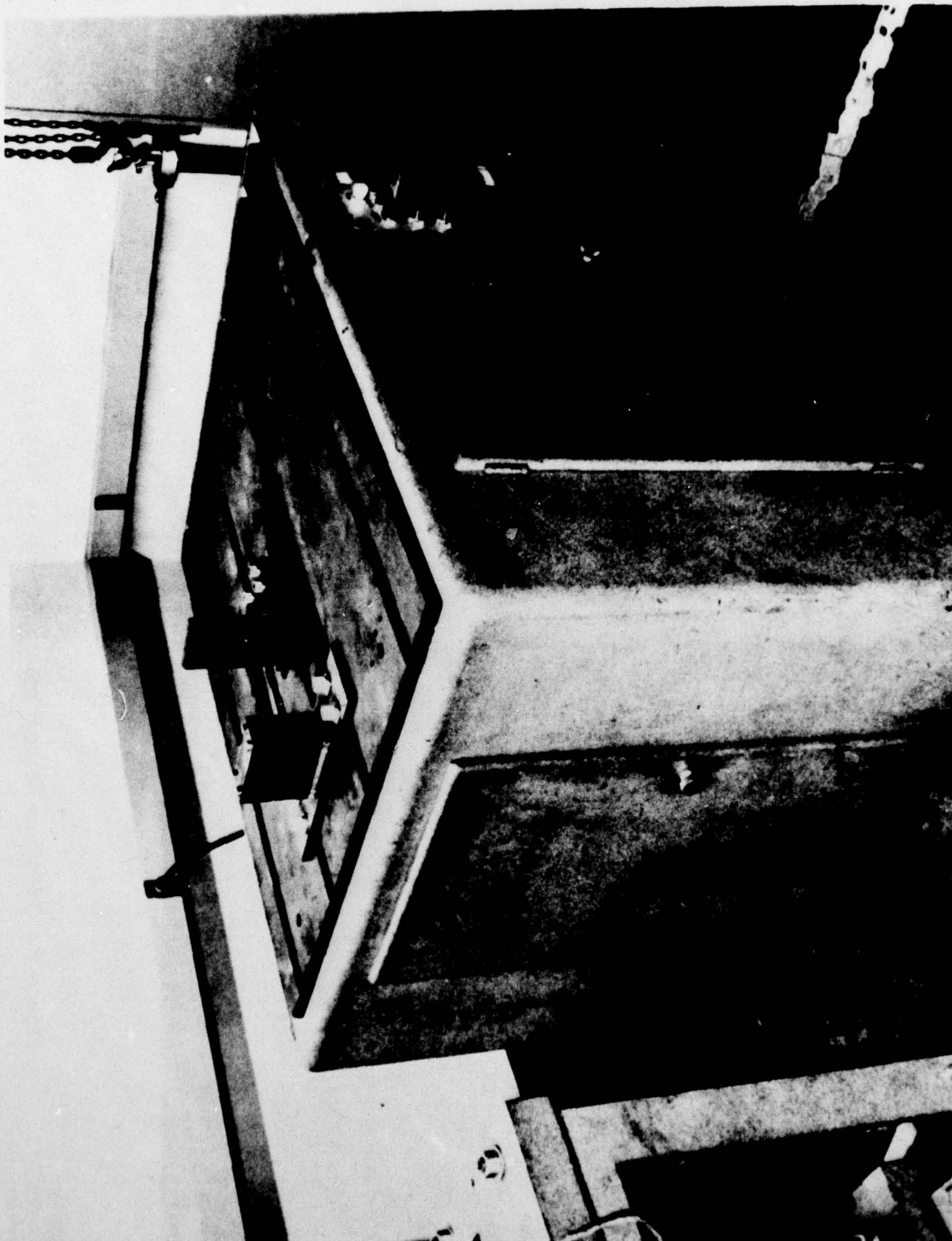


Figure 9. Sontag Fatigue Test Machine Used for Bend Tests

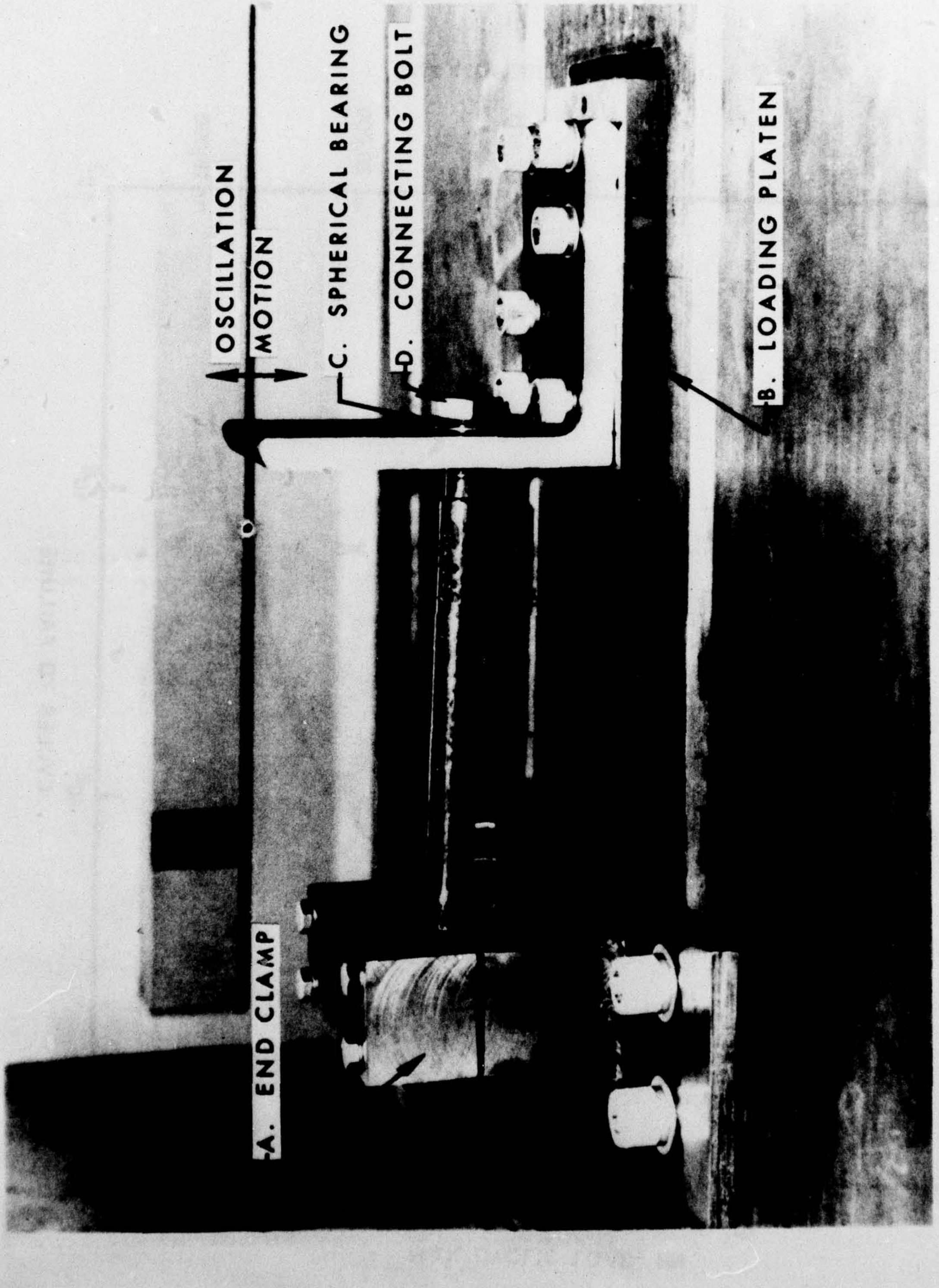


Figure 10. Set-Up for Bending Fatigue Tests in Sontag Test Machine

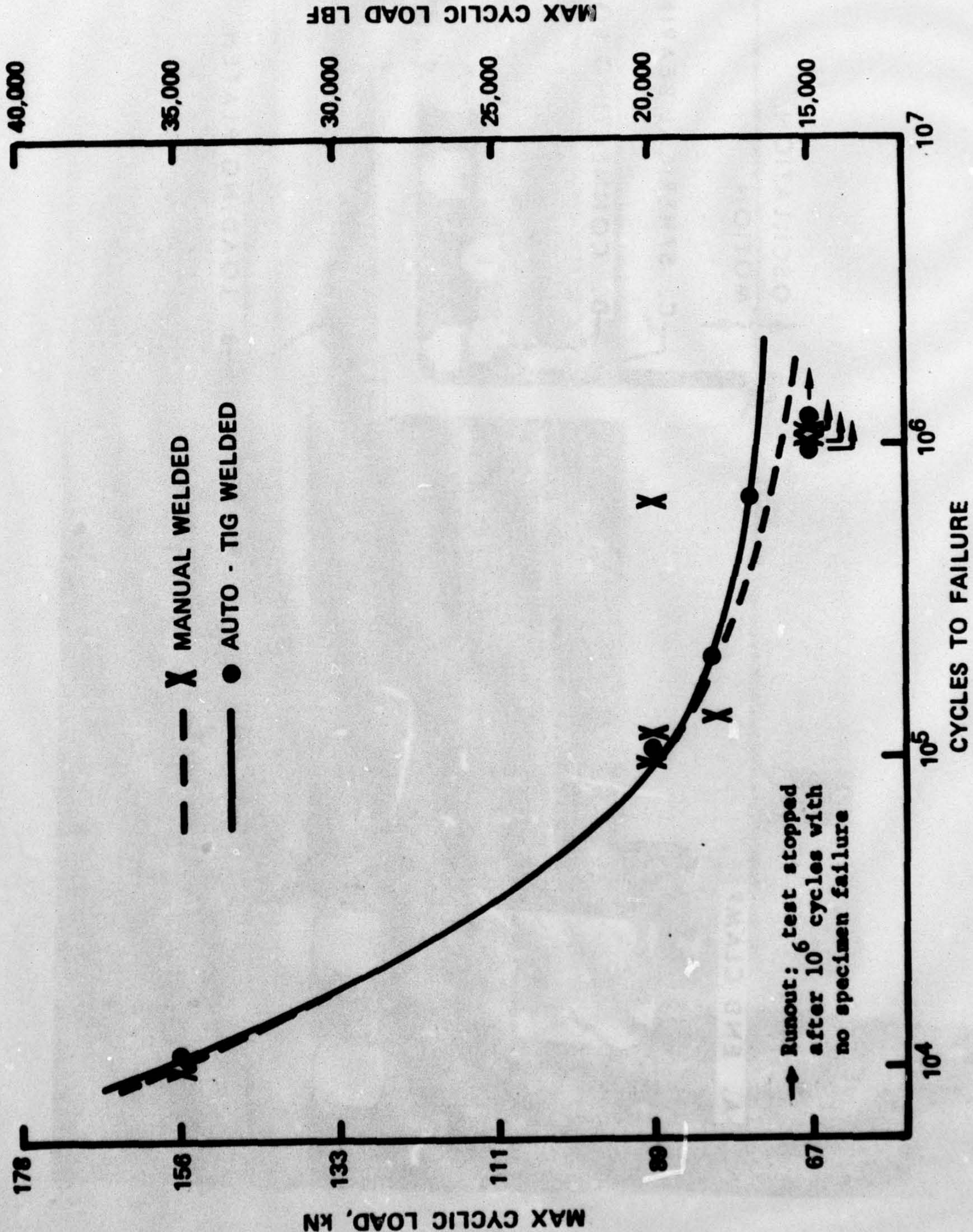
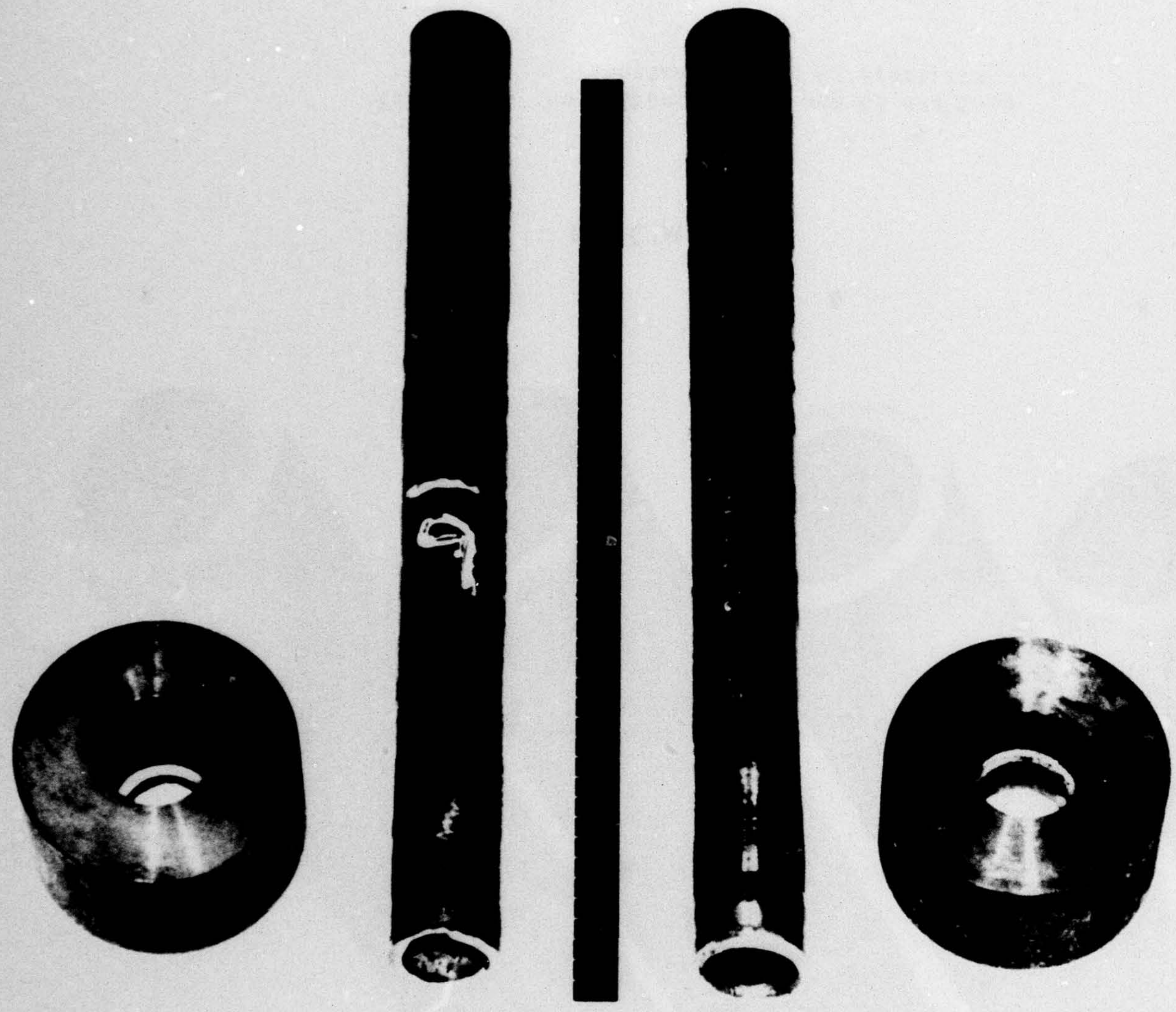


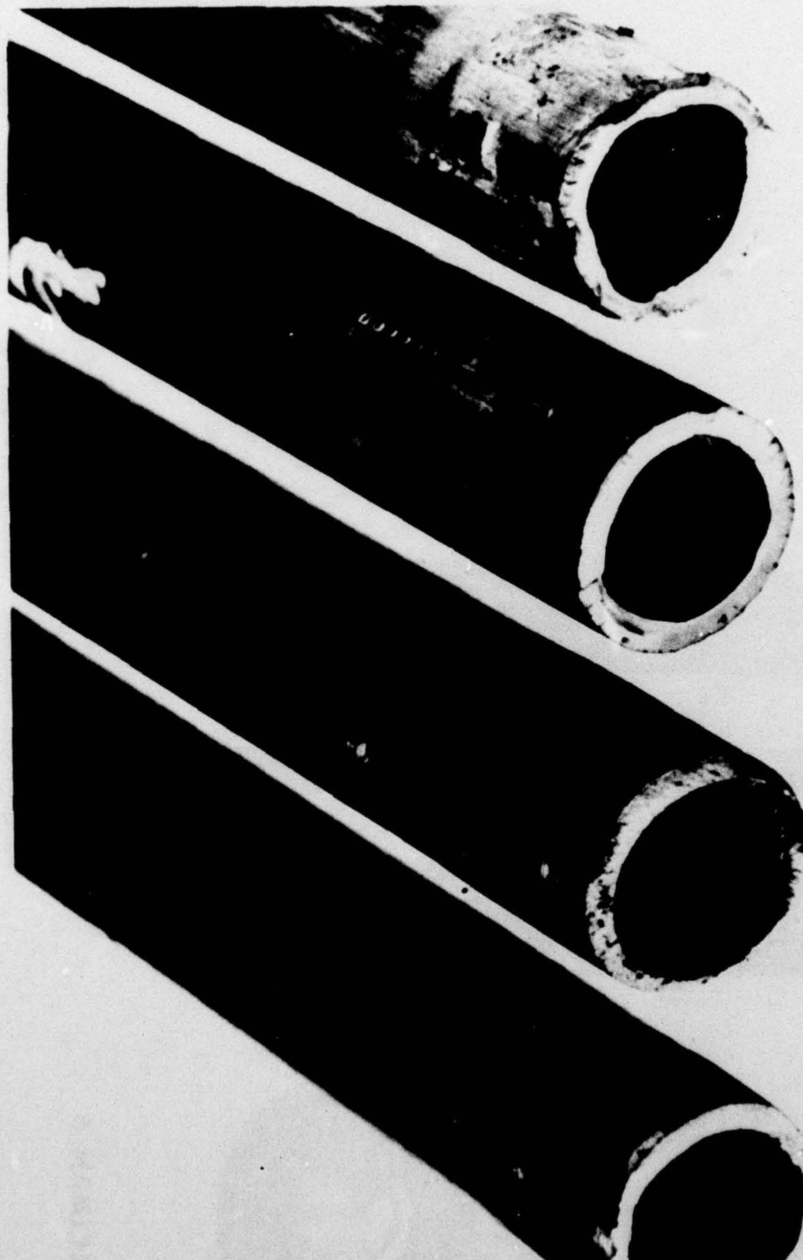
Figure 11. Plot of Test Results - Weld Failures



SPECIMEN 6

SPECIMEN J

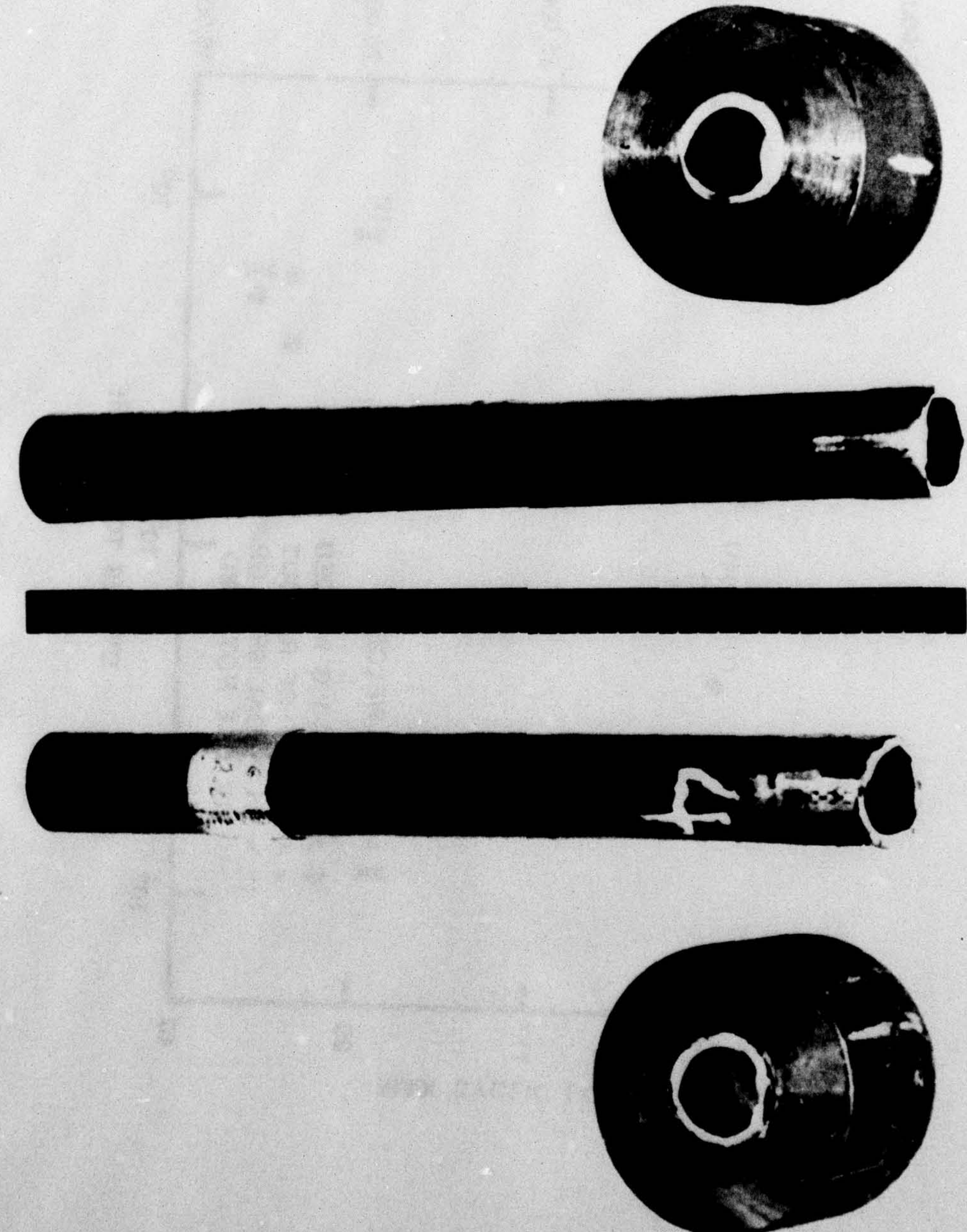
Figure 12. Typical Weld Failures - Manual (Specimen 6) and Auto-TIG (Specimen J) Welded Specimens



R J 6 4

SPECIMENS

Figure 13. Weld (Specimens J and 6) and Tube (Specimens R and 4) Fractures



SPECIMEN 4

SPECIMEN R

Figure 14. Typical Tube Failures - Manual (Specimen 4) and Auto-TIG (Specimen R) Welded Specimens

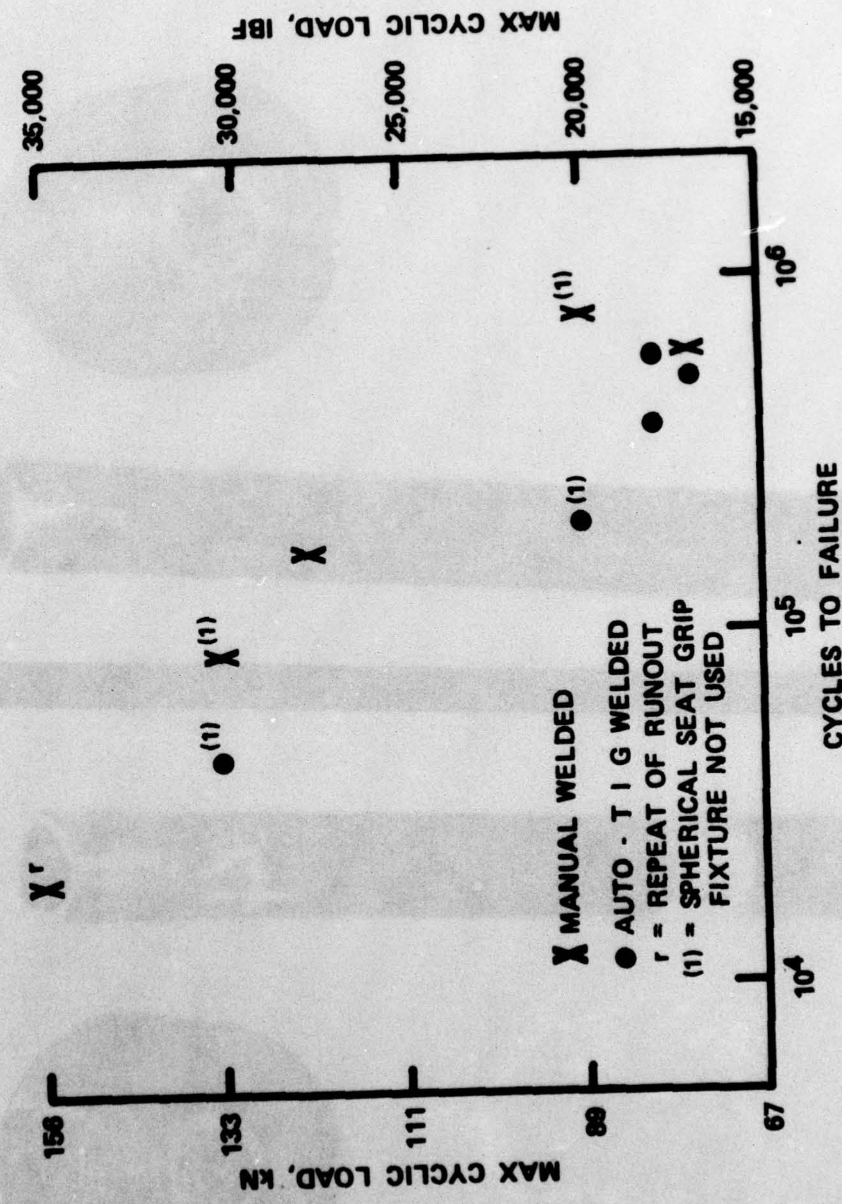


Figure 15. Plot of Tests Results - Tube Failures

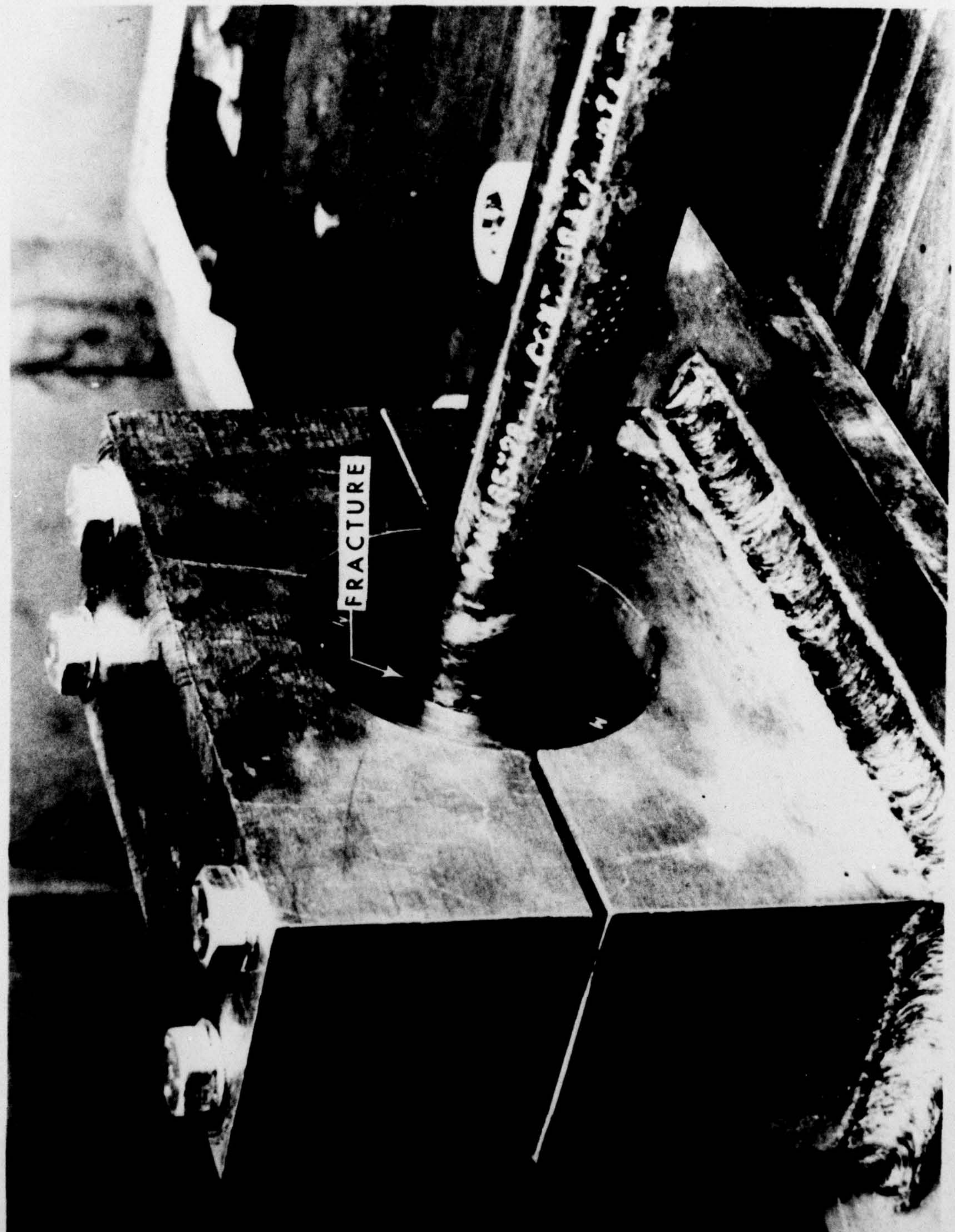


Figure 16. Failed Bending Fatigue Specimen in Test Rig

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